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This report presents a brief overview of potential uses for rf heating of plasmas in mirror devices.[1] While some discussion relating to past experiments will be given, the main emphasis will be devoted to a review of potential experiments in presently existing devices, and devices under construction or planning. We shall also make some predictions for plasmas in mirror reactors. When we discuss rf "heating", we have in mind additional rf related effects, such as the establishment of rf driven thermal barriers, rf plugging of mirrors due to ponderomotive forces, creation of potential wells to trap low energy ions and thereby stabilize DCLC, reactor start-up, etc. However, this list of rf related effects is not complete by any means.

We are interested in the following frequency regimes:

1. ECRH (Electron-Cyclotron Resonance heating, $\omega = \omega_{ce}, 2\omega_{ce}$)
2. ICRF (Ion Cyclotron Range of Frequencies, $\omega = \omega_{ci}, 2\omega_{ci}$)
3. Lower Hybrid Heating ($\omega \underset{>}{\sim} \omega_{LH} \sim \omega_{pi}$)
4. Alfven Wave Heating ($\omega < \omega_{ci}$) (or, TTMP, for transit time magnetic pumping)

In Table 1 we summarize the relevant parameters for three mirror devices of current interest.

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TABLE 1

TYPE	FREQUENCY	LOCATION	FREQUENCY TMX	MFTF-B	REACTOR	COMMENT
ECRH	ω_{ce}	Plug, Thermal Barrier	28 GH	28-55 GHz	55-110 GH	Good for plug heating, A-cell heating
LHH	$\sim \omega_{pi}$	Solenoid	150 MHz	1 GHz	1 GHz	Surface heating if $T_e > 10$ keV
ICRF	ω_{CD} ω_{CD_1} $2\omega_{CD}$	Plug Solenoid	8 MHz 1.6 MHz 3.2 MHz	16 MHz 5.6 MHz 11.2 MHz	32 MHz 20 MHz 40 MHz	Bulk heating in solenoid, or boost N.B. heating in the plug
ALFVEN (TTMP)	$\omega<\omega_{CD}$	Solenoid	-	2.5 MHz	10 MHz	Useful for startup
Power Required	As above	Plug Solenoid	0.5 MW 1.0 MW	2 MW 10 MW	80 MW 200 MW	CW Source $\sim$10 sec for startup

In obtaining these frequencies we used the following reference parameters:

Table 2

	TMX	MFTF-B	REACTOR
n (solenoid)	1×10^{13} cm^{-3}	2×10^{13} cm^{-3}	2×10^{13} cm^{-3}
n (plug)	4×10^{13} cm^{-3}	4×10^{13} cm^{-3}	3×10^{13} cm^{-3}
B_o(solenoid)	0.2 T	0.7 T	2.5 T
B_o(plug)	1.0 T	2.0 T	4.0 T

To provide power for each of these regimes, we have the following power sources available and/or under development.

Table 3

FREQUENCY	POWER PER TUBE	SOURCE	COUPLING
ECRH	200 kW at 28 GHz, cw available 200 kW, cw, at 110 GHz under development (60 GHz possible)	Gyrotron	Waveguides
LHRF	0.5 MW, cw at f $\gtrsim$ 0.8 GHz (2 MW possible)	Klystron	Waveguides
ICRF	0.5 MW, cw (1-5 MW possible)	Triodes, Tetrodes	Coils (ridged waveguides possible)
ALFVEN	1 MW, cw (5 MW possible)	Triodes, Tetrodes	Coils

Some detailed cost estimates regarding these sources can be found in a recent report by Reed, et al.[2] In general, costs for multi-MW units are expected to run $0.50 per watt at low frequencies, $1.0 per watt at the intermediate ($f \sim 1$ GHz) frequencies, and \$3.0 at the highest ($f \gtrsim 28$ GHz) frequencies.

From the comments in Table 1 we see that potential uses for RF include the maintenance of potential barriers at the plug region, heating of electrons in thermal barriers, and heating of the solenoid during reactor start-up. While in the last case, pulse lengths of the order of $5 \sim 10$ sec may be satisfactory, in the first two cases we are considering CW operation. Let us now discuss in some detail the relevant physics issues and potential applications in each frequency regime. We note that extensive theoretical formulas will not be given here; rather, the reader is referred to literature whenever applicable.

Electron Cyclotron Resonance Heating

Electron cyclotron resonance heating in mirrors has been experimentally studied extensively in the past, the prime example being the Elmo program, and in particular, the Elmo Bumpy Torus.(3) In this device the plasma is heated by a set of microwave cavities each of which is in the central region of a pair of magnetic mirrors. By placing many such units end to end, a toroidal configuration is formed. Microwave power is coupled in via O-mode excitation ($E \parallel B_o$) from four 18 GHz klystrons, 15 kW power each. Since the initial temperatures are relatively low, the O-mode radiation is not absorbed; hence the microwaves may bounce around in the cavity many times until they are completely absorbed, presumably via conversion to X-mode radiation ($E \perp B_o$). The leakage of microwaves out of the cavity in the presence of plasma is more than 20 db down from the incident power, and hence most of the power is absorbed within the cavity. The exact mechanism of the efficient power absorption observed experimentally is not well documented. In any case, densities in excess of $10^{12}cm^{-3}$, and temperatures $T_e \simeq 7\ T_i \simeq 400$ eV are obtained during steady state operation.

At higher frequencies, using newly developed gyrotrons more recent results indicate efficient absorption and heating of both the TM-3 tokamak(4) ($f \simeq 60$ GHz) and the ISX-B tokamak(5) ($f \simeq 35$ GHz) at temperatures in the range $T_e \simeq 0.5 - 1.5$ keV, and densities $n \simeq 10^{13}$ cm^{-3}. Because of these results, recently there has been considerable increase in worldwide theoretical effort to obtain a better understanding of ECR heating and the mechanism of wave absorption.(6-9) A summary and application of these results to heating tandem mirrors was recently performed by Porkolab at Lawrence Livermore Laboratory.(10) Very recently, theoretical progress has also been made by applying computer ray tracing techniques to predict the propagation and absorption of waves near the cyclotron resonance layer in an inhomogeneous plasma.(11,12) The results of these studies can be summarized as follows.

a). <u>Wave penetration</u>

For efficient penetration the accessibility condition for a circularly polarized wave (such as emitted by present day gyrotrons) at $\omega = \omega_{ce}$ is roughly given by

$$f \simeq f_{ce} \gtrsim f_{pe} \tag{1a}$$

$$\vec{V}_g \cdot \vec{L}_B < 0 \tag{1b}$$

where $f_{ce} = 28$ B (Tesla) GHz, $f_{pe} \simeq 9000 \left(n_e(\text{cm}^{-3})\right)^{1/2}$ Hz, and V_g is the group velocity of the incident wave (ray-trajectory). The first of these sets a density limit, namely

$$n(10^{13}\text{cm}^{-3}) \lesssim B\ (\text{Tesla}) \qquad (2)$$

and the second condition states that at $\omega \simeq \omega_{ce}$ the magnetic field should decrease in the direction of incident wave propagation, or the X-mode component will be reflected back from the right-hand cut-off frequency before the cyclotron resonance layer. We note that for heating at $\omega \simeq 2\omega_{ce}$ condition 1(b) is not required, and condition 1(a) is improved, to $f_{pe} \lesssim \sqrt{2}\, f_{ce}$.

b). Absorption efficiency

The fraction of power absorbed per pass of the microwave beam is

$$A = 1 - T = 1 - \exp(-\Gamma_o) \qquad (3a)$$

where for the O-mode of propagation,

$$\Gamma_o = 6.4 \times 10^{-7}\ L_B(\text{cm})\ f(\text{GHz})\ T_e\ (\text{eV})\ \frac{n(10^{13}\text{cm}^{-3})}{B^2\ (\text{Tesla})} \qquad (3b)$$

and for the X-mode of propagation

$$\Gamma_x = 1.8 \times 10^{-6}\ L_B\ (\text{cm})\ f(\text{GHz})\ T_e(\text{eV})\ N_z^2\ \frac{B^2(\text{Tesla})}{n\ (10^{13}\text{cm}^{-3})} \qquad (3c)$$

In obtaining Eqs. 3(b) and 3(c) we assumed that $\omega_{pe}^2/\omega^2 \ll 1$. For the general case of $\omega_{pe}^2/\omega^2 \approx 1$ more complicated formulas are required. The conclusion from more detailed calculations[10,12] is that heating of present day mirror devices in the plug region is efficient if we use the X-mode at large angles of incidence (i.e., $N_z \gtrsim 0.5$) but not for the O-mode (at least for initial electron temperatures of a few hundred electron volts). Since the initial radiation emitted by gyrotrons is circularly polarized (i.e., TE_{02} mode), the absorption in one pass is not complete and a cavity should be used for optimizing multi-passage absorption. Alternatively, one might consider developing polarizing converters which would convert the TE_{02} mode (presently generated by gyrotrons) into a linearly polarized mode of propagation. On the other hand, once the temperature exceeds a few keV both the O-mode and the X-mode will be completely absorbed. Hence, for reactor applications ($T_e \gtrsim 10$ keV) the microwaves can be simply beamed onto the plasma column. Alternatively, by injecting the microwave beam along the plasma fan, improved absorption results even at the present low temperature devices.

At present the greatest promise for ECRH lies in the possibility of increasing the plug electron temperature so as to increase the plug potential relative to the solenoid. ECRH is also used to create the so-called thermal barrier region, which would allow a substantial electron temperature difference between the plug and center cell to improve confinement.[13] Further improvement of mirror performance can be achieved by ECR stabilizing of the DCLC mode. This technique relies on the fact that heating electrons locally in the mirror region digs a small potential well which then traps low energy ions, thereby filling the loss cone even at reduced rates of gas throughput. Using this technique, efficient stabilization of the DCLC mode was observed in recent experiments.[14] Such local heating could also be performed by heating a few fast electrons at $\omega = 2\omega_{ce}$, so that the requirements on accessibility could be reduced to $\omega_{pe}^2/\omega_{ce}^2 \lesssim 2$, and a negative magnetic field gradient in the direction of wave propagation (Eq. 1b) is not required. The penalty is higher gyrotron frequency. However, the 110 GHz gyrotrons under development should be satisfactory for this purpose in both MFTF-B and the reactor. Recent reactor designs envisage upwards to 80 MW ECRH heating of the plugs, in combination with neutral beam injection.[13]

Ion Cyclotron Heating

In the case of ion cyclotron heating we consider two regimes, namely heating with the slow wave at $\omega \sim \omega_{ci}$, and heating with the fast wave at $\omega \simeq 2\omega_{ci}$ or heating a minority species at $\omega = \omega_c$ (minority). The relevant frequencies fall in the range $f \simeq 2 - 80$ MHz. The dispersion relation for these waves is given by[15]

$$k_{\parallel}^2 = \frac{k_{\perp}^2}{2(1-\Omega^2)} \left\{ -(1-\Omega^2) + \frac{2\omega^2}{k_{\perp}^2 V_A^2} \pm \left[(1-\Omega^2)^2 + \frac{4\Omega^2\omega^4}{k_{\perp}^4 V_A^4} \right]^{1/2} \right\} \tag{4}$$

where the upper (plus) sign designates the slow (ion cyclotron) wave and the lower (minus) sign designates the fast (magnetosonic) wave and $\Omega = \omega/\omega_{ci}$. The theoretical investigations regarding the exact heating mechanisms can be found in the literature.[15-18] Of relevance in connection with the fast wave propagation is the minimum machine size to fit a given mode; this corresponds to the condition $k_{\parallel} = 0$, or

$$n(\mathrm{cm}^{-3})\, a^2(\mathrm{cm}^2) > 5 \times 10^{15} \left(\frac{m_i}{m_{iH}}\right)\left(\frac{\omega_{ci}^2}{\omega^2}\right) \mathrm{cm}^{-1} \tag{5}$$

where n is the density, a the plasma radius, m_{iH} the mass of hydrogen ion, and $\omega_{ci} = eB/m_i c$ is the ion cyclotron frequency of the ion species under consideration. Thus, magnetosonic wave propagates only in a sufficiently dense and large plasma column. Early experiments in the 1960's showed successful application of the slow wave to heating the B-66 mirror device at the Princeton Plasma Physics Laboratory.[19,20] Similarly, ion-cyclotron heating of the C-Stellarator showed heating of ions to temperatures of almost 1 keV.[21] In these experiments the wave was launched via a Stix coil placed in the magnetic mirror region ($\omega < \omega_{ci}$) and it damped as it propagated to the magnetic beach region ($\omega \approx \omega_{ci}$). Concommitant heating of the ions was also observed. There have been also successful experiments using the slow wave in recent stellarator experiments in the USSR and Japan.

More recently, using the fast wave efficient heating of tokamak plasmas at $\omega \gtrsim \omega_{ci}$ has been demonstrated.[22-24] In this case heating is achieved near the ion cyclotron resonance layer via absorption by a minority species such that $\omega = \omega_c$ (minority) and consequent collisional relaxation of this energetic component leads to heating of the majority (D^+) ions. To date both H^+ and $^3He^{++}$ have been used for minority ions. In principle, ion heating may also be achieved by the majority species (D^+) at $2\omega_{ci}$ due to finite ion Larmor radius effects. However, to date a clear experimental proof of this absorption mechanism does not exist. In particular, efficient absorption at $2\omega_{CD}$ depends on finite β_i. Finally, heating of electrons may be effective at high electron temperatures ($T_e \gtrsim 5$ keV) due to electron Landau damping and transit time magnetic pumping when the wave phase velocity is such that

$$\frac{\omega}{k_{\|}} \approx v_{te}.$$

Very recently new programs in ICRF heating of mirror devices have been initiated in the Phaedrus mirror device at the University of Wisconsin,[25] and also at the United Technologies Research Center. The object of these experiments is to demonstrate the effectiveness of ICRH heating of mirror and tandem mirror devices, as well as to study rf created thermal barriers, rf trapping, and rf plugging. In particular, 1 MW of slow wave heating of the end plug will be used on Phaedrus to study the feasibility of an rf driven neutral beam sustained tandem mirror concept. Favorable results from this experiment could significantly impact the end plug energy available in MFTF-B (i.e., RF heating could double the 80 keV beam energy planned for this experiment). One might also consider ICRF heating of the solenoid ions. Fast wave heating will also be tested for heating of both ions and electrons in Phaedrus. Another potential use of ICRH is to form a thermal barrier region locally by expelling ions. Finally, application of ICRF in the mirror region will be studied both on Phaedrus and the United Technologies Research mirror for the purposes of RF plugging of mirrors via the ponderomotive force, which for ions is:

$$F = \nabla\psi = -e^2 \nabla E_+^2/4m_i(\omega^2 - \omega_{ci}^2).$$

Initial results on Phaedrus already show an effective heating of ions from 200 to 400 eV upon application of 45 kW of ICRF power via the slow wave at $\omega = \omega_{ci}$.[25] No deleterious effects upon plasma confinement were observed in this experiment. This is presumably due to the slow diffusion produced by an electromagnetic wave as opposed to the fast losses produced by electrostatic waves characteristic of the DCLC instability (which scatter particles out into the loss-cone).

Finally, we mention the possibility of using ICRF for purposes of plasma start-up. In particular, assuming a reactor of length 50-100 meters, a plasma radius of $a \approx 1\text{m}$, a central cell energy of $T_e \approx T_i \approx 50$ keV, and a central cell confinement time of about 1 sec, we would need 200 MW of auxiliary power for start-up (i.e., this much power would have to be applied initially for $t \sim 5$-10 sec to form the central cell target plasma). One possible way is to use ICRF to provide this power. For example, at temperatures $T_i \approx T_e \gtrsim 10$ keV, the fast wave would be absorbed efficiently either by second harmonic absorption, or by electron Landau damping (if $\omega/k_{\|} \approx V_{te}$).

Lower Hybrid Heating (LHRF)

In this case we consider heating near the ion plasma frequency, namely $f \sim 1$ GHz. Lower hybrid heating has considerable technological advantages over other frequency regimes, namely waveguide coupling and available cw power at the MW level.(1) However, there are several shortcomings in the physics area which must be kept in mind when we consider application of this regime to mirror devices:

a) At high temperatures $T_e \approx T_i > 10$ keV, the absorption of the slow wave is so strong that, at least based on quasi-linear theory, strong surface absorption is expected.

b) The energy tends to be absorbed by electrons on the tail of the distribution function ($\omega/k_{\|} \gtrsim 3\, V_{te}$) and this range of energies is not well confined in tandem mirrors.

c) Fast wave propagation would also be effective as an electron heater at high electron temperatures ($T_e \gtrsim 5$ keV), however, large plasma densities are needed in the immediate vicinity of the waveguide mouth for good accessibility. This may lead to rf breakdown at high power levels in front of the waveguides. However, this concept remains to be tested in future experiments.

d) Nonlinear effects are expected to be important, and the resulting plasma reaction is difficult to predict theoretically. We have to wait for further experimental results from forthcoming tokamak experiments regarding this problem. In case of favorable results, initial test experiments at the 1 MW level should be considered on existing tandem mirrors, such as TMX.

On the other hand, we should recognize some potential advantages of LHRF in special applications:

a) LHRF could pump electrons along B by electron Landau damping of the tail. This may find special uses in some thermal barrier schemes. For good axial localization of the rf energy we should consider frequencies such that $\omega_{ce} > \omega >> \omega_{pi}$, so that the resonance cone angle with the magnetic field is not too shallow.[26]

b) Creation of fast ions, and strong interaction with an energetic neutral (ion) beam energy has been observed upon interaction with LHRF.[27] Hence, if penetration could be achieved, this technique would also allow efficient pumping of the ion (neutral) beam energy in the plugs in a tandem mirror.

Alfven Wave Heating

Alfven waves may be launched at frequencies $\omega < \omega_{ci}$, and the compressional Alfven wave (which is the low-frequency continuation of the fast magnetosonic wave) could be used to heat electrons by electron

Landau damping and transit time magnetic pumping (or electron TTMP).[16] The dispersion relationship is given by

$$\omega^2 = (k_{\parallel}^2 + k_{\perp}^2)\ v_A^2$$

where $v_A = c(\omega_{ci}/\omega_{pi})$ is the Alfven speed. The power absorption rate is given by

$$P = \frac{\omega\beta_e\ N_{\perp}^2}{16\pi^{1/2}} \quad \left|\frac{\omega}{k_{\parallel} v_{te}}\right| \quad |E_y|^2 \exp\left[-\omega^2/k_{\parallel}^2\ v_{te}^2\right] \tag{7}$$

where $\beta_e = 8\pi n_e T_e/B^2$ is the electron beta, $N_{\perp} = c\ k_{\perp}/\omega$, and $v_{te} = (2\ T_e/m_e)^{1/2}$ is the electron thermal velocity. For reasonable strength electric fields (a few hundred volt per cm) the power absorption is sufficiently weak locally so that bulk electron heating could be achieved by a set of phased-array coils adjusted so that the condition $\omega/k_{\parallel}v_{te} \simeq 1$ (i.e., $0.5 \gtrsim \omega/k_{\parallel}v_{te} \lesssim 2$) is maintained. Estimates indicate that a wave launched in the solenoid in a reactor plasma could be absorbed in one pass along the solenoid. By varying the phases of the coils, the temperature could be raised from a few keV initial temperature to $T_e \simeq 50$ keV in times comparable with the energy confinement time ($\tau_E \simeq 1$ sec). The frequencies used for this heating technique would be in the range of 1-10 MHz. The condition for exciting this wave is the same as Eq. (5); hence, this mode could be excited only in sufficiently large and dense plasmas, such as MFTF-B or in a reactor. It is proposed that this type of heating be tested in MFTF-B. Due to the lack of sufficiently large plasmas, to date no experiments have been performed using this wave. However, because of the relatively low cost of rf generators in this frequency range, and because large powers are available upon demand (i.e., a $\sim$ 5 MW CW tube can be developed) this frequency regime appears a favorable one for "start-up" heating of the solenoid until α-particle heating becomes substantial. Rough estimates indicate that several hundred MW may be needed for this purpose for pulse lengths up to 10 sec.

Conclusions

In this report we considered briefly potential uses of rf heating in tandem mirror devices. Several frequency regimes appear favorable for a number of different purposes such as heating solenoids, boosting neutral beam energies, forming thermal barriers, stabilizing instabilities, producing ponderomotive forces, for stoppering, etc. The present list is obviously too brief, and with time, we expect to see new potential applications of rf power for improving tandem mirror performance.

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